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STRATEGIC PETROLEUM RESERVE (SPR)
GEOLOGICAL SUMMARY REPORT
WEEKS ISLAND SALT DOME

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ABSTRACT

A portion of the Weeks Island Salt Dome in southern Louisiana has been purchased by the Department of Energy for the Strategic Petroleum Reserve Program. The complex will be a crude oil storage facility converted from a conventional underground salt mine. This summary of the geotechnical investigations undertaken by several organizations discusses site geology, material properties of the salt, the condition of the oil storage area, the status of other activities in the salt dome, and recommendations.

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STRATEGIC PETROLEUM RESERVE (SPR)
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INTRODUCTION

Congress authorized the creation of the Strategic Petroleum Reserve (SPR) in the Energy Policy and Conservation Act of 1975. The objective of the SPR is to provide for the storage of at least 750 million barrels of crude oil to minimize the effects of possible severe oil supply interruptions.

Salt domes were chosen as storage sites in part because of the low permeability of salt and the economic advantage of large underground storage caverns. The storage sites are located in the Gulf Coast region of Texas and Louisiana and are accessible to tanker ports and major pipelines. The salt domes include Bryan Mound in Texas and Bayou Choctaw, West Hackberry, Sulphur Mines, and Weeks Island in Louisiana. At four of the sites, oil will be stored in existing caverns in the salt that were formed during commercial brine production. Some caverns have also been used for storage. In addition, new caverns will be created specifically for the SPR program. At the fifth site, Weeks Island, oil will be stored in an abandoned room and pillar salt mine.

The storage capacity of Phase I of the project is 248 million barrels. The oil will be stored in existing caverns and the mine. Currently 91.7 million barrels of crude oil are stored. Phase II will involve leaching of additional caverns with added storage space and 290 barrels. DOE is presently considering a Phase III program plan which will provide an additional 190 barrels of storage capacity.

Sandia National Laboratories, at the request of DOE, is providing geotechnical support to the SPR. This includes site characterization, engineering design assistance and evaluation, laboratory and bench scale testing of salt cores from SPR sites, monitoring and interpretation of field events, instrumentation evaluation and development, and technical support for the leaching program.

As a part of the site characterization, four site geological characterizations are currently being conducted. The following contractors are providing geologic support to Sandia.

| | |
|----------------|---|
| Bryan Mound | D'Appolonia Consulting Engineers, Inc. |
| West Hackberry | Woodward-Clyde Consultants |
| Sulphur Mines | Law Engineering Testing Company |
| Bayou Choctaw | Acres American, Incorporated |

The contractors have been asked to do the following:

1. Acquire, compile, evaluate and interpret the existing data pertinent to the geological characterization of the individual SPR sites.

2. Characterize the surface and near-surface geology and hydrology with respect to its impact on SPR surface facilities.
3. Define the geological, hydrological and geophysical characteristics of the **caprock**.
4. Define the geometry and geology of the salt dome.
5. Assess possible effects of natural events (hurricanes, earthquakes, etc.) on site geology,
6. Assist in the planning of Phase 2 of site characterization if deemed necessary by Sandia after the completion of Phase 1 efforts.
7. Assist in the planning and development of a long-term monitoring plan to ensure the integrity of the stored crude oil over the life of the SPR program.

This paper summarizes the site characterization that has been completed on Weeks Island. The majority of the geotechnical work has been done by Acres American Incorporated (Acres).

CONCLUSIONS AND RECOMMENDATIONS

The Weeks Island SPR site has been adequately characterized by previous geotechnical efforts. Two possible problem areas at the site are:

The wet drift - An area of wet salt was encountered immediately west of the oil storage area during routine blasting of the planned access drift to the **Markel** Mine. Considerable grouting has been done to try to stop the leak. A grouting program is currently underway, and should be evaluated when completed. A bulkhead constructed to close off the wet drift allows passage into the wet drift for observation and grouting. The bulkhead can be completely shut, in case of severe sudden water inflow.

The service shaft - The service shaft was completed in 1902 and the effectiveness of seals and condition of the concrete liner are unknown. The shaft is not plumb, perhaps indicating some movement in the shaft. Acres recommended testing of the concrete and the installation of pressure taps to monitor water pressure behind the shaft. However, no serious problems in the service shaft have occurred to date. It has been decided not to disturb the shaft by installing pressure taps. The hazardous consequences of these problems would be flooding or damage to the oil recovery equipment.

The following recommendations were **made** by Acres in 1977 (1/11) and 1979 (12/16). Sandia's comments are included.

| <u>Acres Recommendations</u> | <u>Sandia's Comments</u> |
|---|--|
| 1. That further studies be undertaken to determine the cause and mechanism of blowout formation in dome salt with the objective of developing a methodology for predicting blow outs in any mining area. Once identified, such high risk areas could be avoided during mining or possibly some action taken to alleviate the risk. | (1,2) Since the recommendation was made, Dames and Moore⁶ and Sandia^{18,19} have conducted studies of blowouts. Dames and Moore concluded that precautions in mining can reduce the possibility of blowouts. Sandia¹⁸ concluded that it is most unlikely that an outburst could connect a new mine to an existing mine. |
| 2. That no mining of a new lower mine level beneath the proposed oil repository be initiated until recommendation (1) has been satisfied. | |

3. That sonar logging be performed in brine wells No. 1 and 2 (Fig. 6) to determine the actual configuration of the solutioned caverns. Depending on the results of sonar logging, solution mining may have to be curtailed or controlled to ensure the safety of the oil repositories.
 - (3) Brine well 2, 1400' from the oil storage area was sonar surveyed in May 1978. The well is about 100-150' in diameter from -325' to -1510'. Brine well 1, farther from the mine than well 2 has not been sonar surveyed. Sandia does not feel that it is imperative to sonar survey well 1 at this time. However, if Morton Salt Company does sonar survey either well at any time, Sandia recommends that DOE request copies of the survey.
4. That both shafts be scaled, pressure tap readings taken in the production shaft and pressure taps installed in the service shaft and read to determine the groundwater pressure distribution behind the shaft linings, and a grouting program conducted in the shafts if deemed necessary on the basis of the results obtained to ensure the continuing stability of the shafts.
 - (4) The utility of the information obtained from pressure tap readings is uncertain.
5. That an attempt be made to locate and, if required, seal boring No. 16 located approximately 100 feet south of the mine (Fig. 6).
 - (5) Sandia agrees.
6. That an attempt be made to locate and seal the 5 known borings (Fig. 9) and any other borings made in the floor of the lower level and that large pillars (of the order of 400-foot diameter) be left in any new level mine around those holes that 'cannot be adequately sealed to ensure no leakage of oil into the new level.'
 - (6) Borings made within the mine have been located and sealed with MSHA approval¹².

7. That monitoring of all oil and gas drilling around the perimeter of the dome is continued to assure that no holes will be drilled that could possibly affect stability and containment. (7) Sandia agrees.
8. That the mine conversion scheme (as presented in Section 5 of Acres, 1977) be assessed against project conversion cost schedules and confining parameters. (8) No comment.
9. That a monitoring and inspection program (as outlined in Section 7 of Acres, 1977) be implemented and continued while oil is in storage to assure
- (a) the integrity of the repository for oil withdrawal: (b) the safety and stability of any new mine workings in proximity to the oil repository: (c) the integrity of the shafts.
- (The program should include monitoring of surface subsidence, shaft and bulk-head inspection and monitoring, convergence and pillar deformation in the new Morton Salt Company mines, measurements of pillar and web stress changes in the new mines, and monitoring of the brine wells.)
10. That the possibility of detonation of oil vapor within the mine be further studied and, if the risk is confirmed, that either the method of filling the mine with oil or the atmosphere in the mine during filling or both are so controlled that the air/vapor mixture at no time falls within the flammable limits. (10) The mine has been filled with inert gas since the recommendation was made.

11. That further detailed analyses of the modification of pillar stresses with time be performed to provide theoretical confirmation of the conclusion (based on observations in the mine and the analyses described in this report) that pillars do eventually achieve a stable configuration.

12. The construction of concrete bulkheads to isolate the manifold room from the Markel Mine. Since emergency access to the service shaft from the Markel Mine **must** be maintained, the bulkheads must incorporate **manways** which can be quickly closed off in the event of an emergency. The location of the bulkheads should be determined by joint consultation between DOE and Morton Salt Company, but to minimize interference with mining operations, they will probably have to be constructed in the upper and lower by-pass ventilation drift. All materials and equipment necessary to permanently seal the **manways** should be maintained at site, preferably close to the bulkheads, and the procedures to be adopted in the event of an emergency clearly established.

(11) **Sandia**^{18,19} did additional analysis in 1979. Results from further detailed analyses would not be worthy of the effort at this time.

(12) Sandia recommends that the ability to install the bulkheads on short notice be ascertained.

13. The purchase and maintenance on site of grouting equipment and materials suitable for operation within the fully equipped service shaft and the execution of a maintenance contract with a specialist grouting contractor to provide skilled operators at short notice to carry out emergency remedial grouting work in the service shaft in the event that any leakage through the lining or past the seals should develop. It would be advisable for the grouting contractor's staff to become completely familiar with the site conditions so that in an emergency work can proceed with the minimum delay.
- (13) Sandia recommends that the ability to perform grouting operations on short notice be ascertained.
14. The establishment of routine inspections of the service shaft, both visually and by precision survey methods, to monitor for any deterioration of the service shaft lining, signs of incipient leakage or for any displacement of the shaft. The visual inspections should be conducted on a weekly basis and the survey on a monthly basis. Procedures to be adopted in the event of any changes in the condition of the shaft should be clearly established.
- (14) Observations should also be recorded.

15. The establishment of routine monthly inspections of all the drifts between the production shaft, manifold room and the Markel incline bulkhead as long as the Markel Mine is in operation and the establishment of arrangements with the Morton Salt Company to ensure that DOE is kept informed of progress and any problems encountered in the Markel Mine. (15) Observations should also be recorded.
16. The condition of the Markel Mine and associated drifts should be reviewed when the mine is abandoned by Morton Salt Company and procedures established at that time for continuing monitoring of the-mine, drifts and production shaft. (16) Sandia agrees.

The Ralph M. Parsons Company has recently completed a detailed safety/hazard analysis of the Weeks Island SPR site. The study included system descriptions and analysis, and possible failure modes and effects. The report also includes special studies concerning leakage at bulkheads, service shaft headframe fire hazard, installation of equipment and piping in the service shaft after fill, and the crude oil system (fill, withdrawal, and recycle). Parsons includes recommendations and cost estimates.

GEOTECHNICAL SUMMARY

Weeks Island is located south of New Iberia, Louisiana in south-central Louisiana. The "island" rises up to 170 feet above the surrounding **marshland** and is about two miles in diameter. Salt was discovered in 1897. Production of salt began in 1902 from a room and pillar underground mine. Salt and brine are currently being mined by Morton Salt Company. The storage capacity at the Weeks Island SPR site is 75 million barrels of crude oil.

Regional Geology

South-central Louisiana lies within the Gulf Coast section of the coastal plain physiographic province. Structurally, the area is on the northern flank of a gulfward-dipping geosynclinal basin. The regional axis of the geosyncline roughly corresponds to the coastlines of Texas, Louisiana, Mississippi, Alabama and Florida. The stratigraphic record indicates that the geosyncline has been subsiding slowly since **Cretaceous** time as the area received a voluminous accumulation of sediments⁷. Growth faults normal and down to the south are typical. The faults are gradational and concurrent with deposition.

Weeks Island is one of the Five Island salt domes aligned in a northwest-southeast direction in southern Louisiana. The islands include Jefferson, Avery, Weeks, Cote Blanche and Belle Isle (Fig. 1).

Surface

Existing reports discuss in detail the topography, hydrology and soils of Weeks Island. The topographic expression of Weeks Island salt dome is two miles in diameter. The maximum elevation on the island is 170 feet. Weeks Bay, an extension of Vermillion Bay, is on the west side of Weeks Island. The remaining sides are bordered by marsh (Fig. 1). The topography is **hilly** (Fig. 2) with gullies 20-60 feet deep in one area of the island⁷. A topographic scarp trending **N20°E** and facing east crosses the middle of the island and probably represents the surface **expression** of a boundary shear zone in the salt. To the east of the scarp is an internal valley that crosses the island and is probably also related to the boundary shear zone. The valley includes a line of sink-hole lakes. Some of the other aligned valleys may also represent shear zones in the salt². The lakes could reflect subsidence caused by surface solutioning of the **salt**^{15,20,4}. Springs are common on the northern slopes of the island.

The island is on the northern edge of the **Atchafalaya-**Vermillion estuary complex. The bays are shallow and rimmed on the north by brackish and intermediate waters and on the south by salt marshes. Bay waters are **brackish**⁷. The most important navigational body of water in the area is the Intracoastal Waterway. Waterways, watersheds, precipitation and surface water

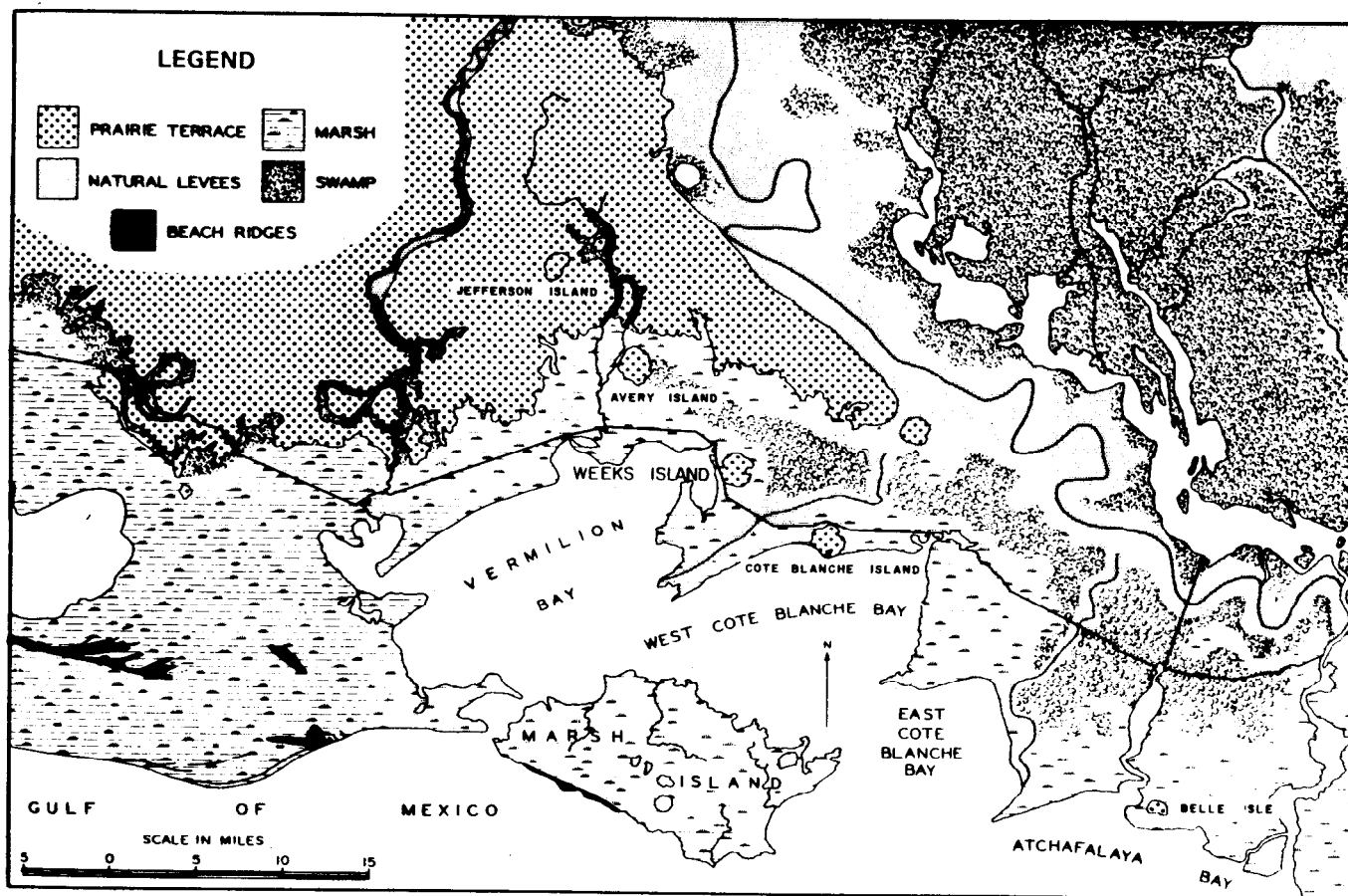


Figure 1 - PHYSIOGRAPHIC MAP OF CENTRAL COASTAL LOUISIANA (Modified from Van Lopik, 1955 in Federal Energy Administration Strategic Petroleum Reserve Office, 1976, Draft Environmental Impact Statement for Weeks Island Mine)

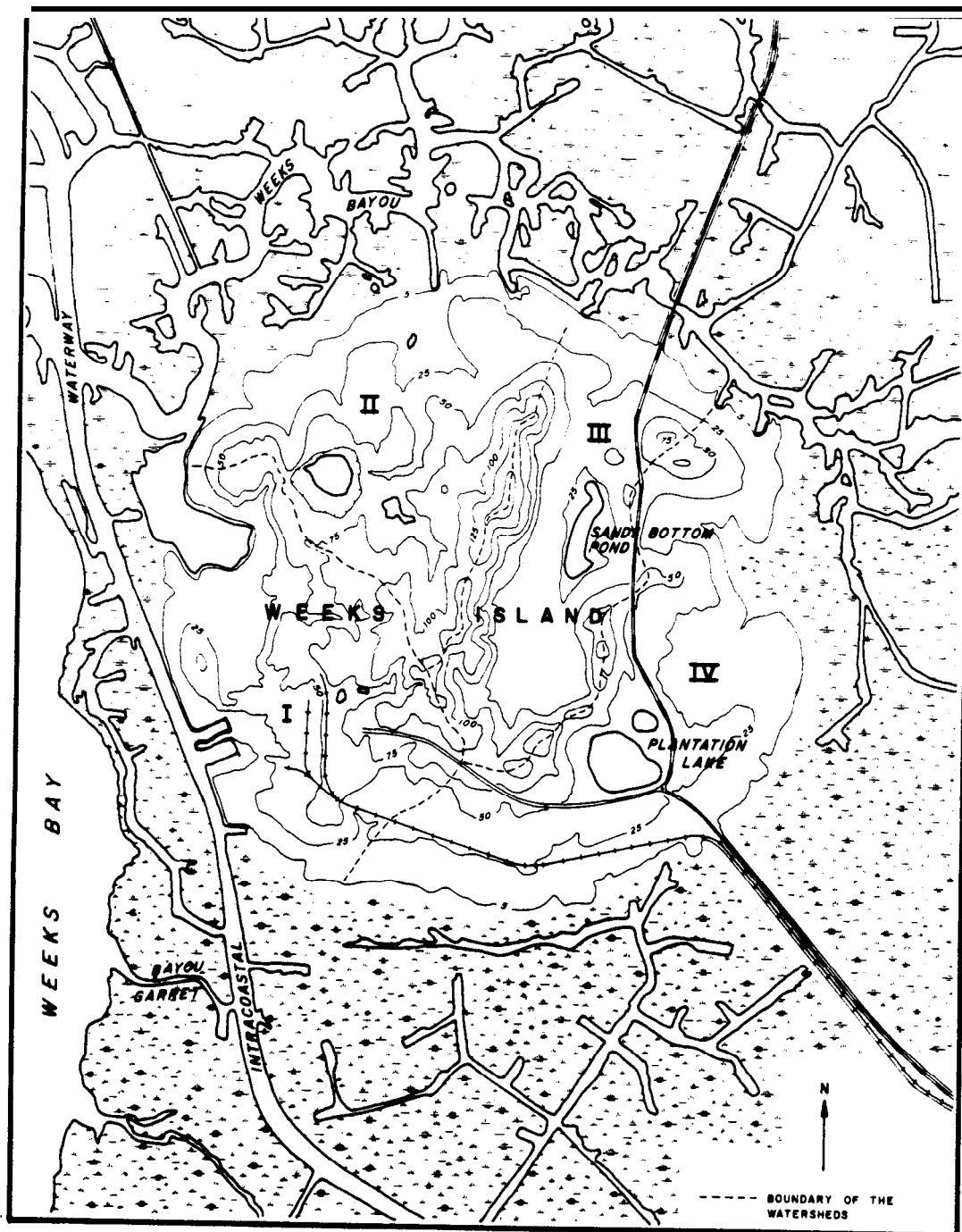


Figure 2 - WEEKS ISLAND TOPOGRAPHY AND WATERSHED BOUNDARIES
 (From Federal Energy Administration Strategic
 Petroleum Reserve Office, 1976, Draft Environmental
 Impact Statement for Weeks Island Mine)

runoff are discussed in detail in the Environmental Impact Statement volumes. Surficial sediments are brownish-yellow, loamy silts and clays varying in thickness from a few inches to 30-40 feet. Ferruginous sands with bands of **chert** pebbles are exposed on the southern sides of ridges and in some deep gorges'.

Near Surface to Top of Dome

Information on the sediments from the near surface to the top of salt is limited. Exploratory drilling has not revealed the presence of a **caprock** typical of many Gulf Coast domes. Except for a few minor pockets of methane, no cavities associated with **caprock** formation have been found at the top of the salt^{6,7}. Depth to salt in the mine area is 100-200 feet from the surface. A few feet of organic clay overlies the salt. Above the clay are sands of the Pleistocene Praire formation. A stratigraphic section of the sediments overlying the salt is shown in a 1901 sketch of the area adjacent to the service shaft (Fig. 3). The **completion reports** of the vent hole and two oil fill holes by **Fenix & Scisson**^{9,10,11} indicate gumbo shale/sand to within 10-20 feet of the salt with sand directly overlying the salt (Fig. 4). The reports indicate top of salt at 197 feet below the surface or -102 MSL at the vent hole and -135 MSL at both fill holes.

The Chicot formation of Pleistocene age is the principal aquifer in the **area** (Fig. 5). The piezometric surface in the Chicot, approximately at sea level near Weeks Island, slopes slightly to the northwest towards an **inland depression** caused by heavy withdrawals around Lake Charles⁷. **Harder and others**¹³ showed that near the coast, the **fresh water of the Chicot gradually becomes saline** at 300-600 feet. **Whitman and Kilburn**²¹ showed that many of the smaller localized shallow sands that overlie the "upper sand unit" contain saline water. Some are fresh, however, and provide water for local areas. The water-bearing sands above the salt at Weeks Island probably represent the shallow sand aquifers of the **Chicot**⁷.

Levels of fresh water ponds on the island may vary from 15-60 feet above sea level. That suggests that much, if not all, of the shallow **ground water** is perched above impervious horizons at varying elevations⁸.

Deeper Sediments

Approximately 15,000 feet of Miocene, Pliocene, and Pleistocene sediments are present adjacent to the dome. The Miocene and Pliocene sediments consist of transition and shallow marine **facies**⁷. The upper third of these sediments are Pleistocene in age and include from oldest to youngest the Williana, Bently, Montgomery and Praire formations. Each unit grades from sands and gravels at the base to finer sediments at the top.

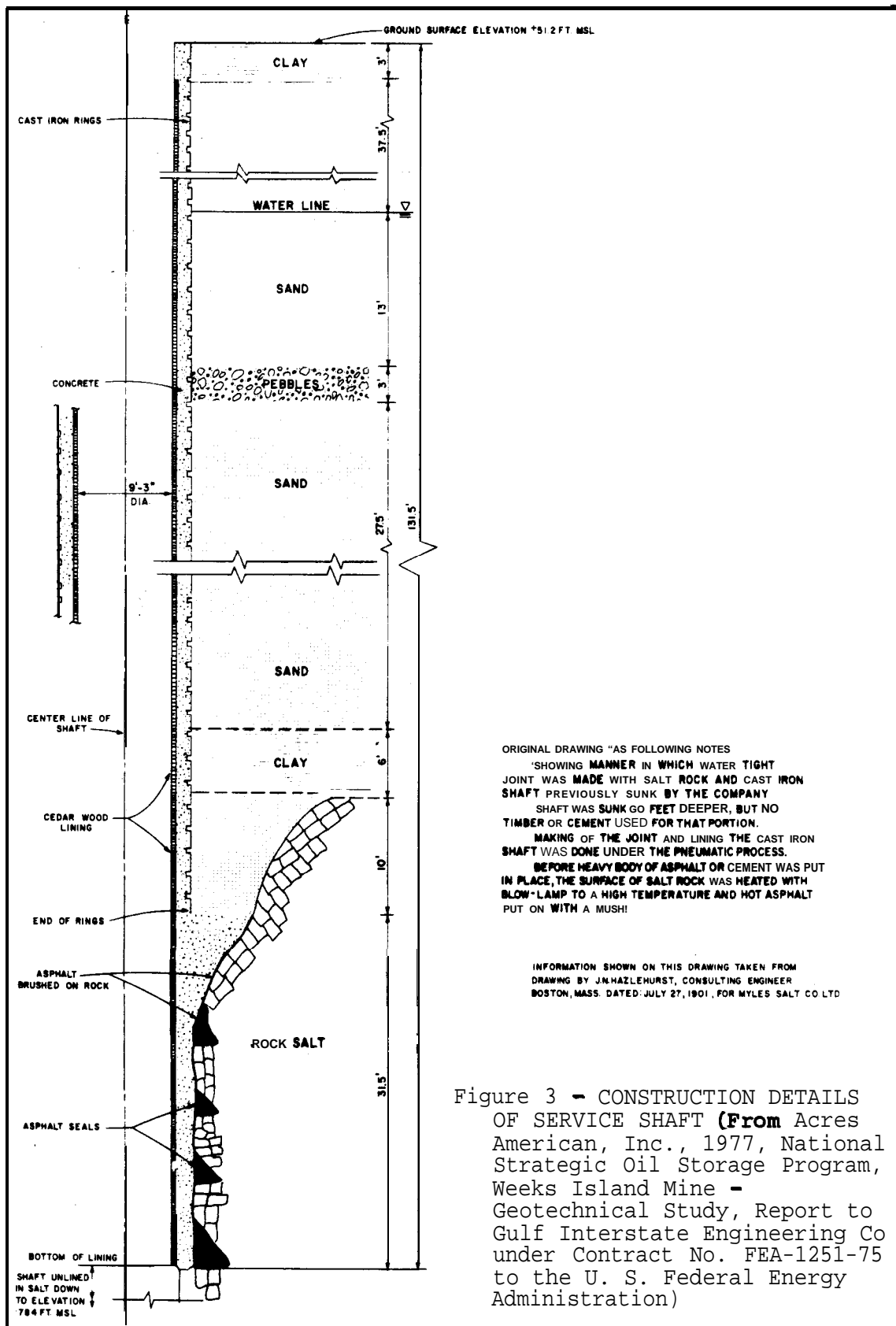


Figure 3 - CONSTRUCTION DETAILS OF SERVICE SHAFT (From Acres American, Inc., 1977, National Strategic Oil Storage Program, Weeks Island Mine - Geotechnical Study, Report to Gulf Interstate Engineering Co under Contract No. FEA-1251-75 to the U. S. Federal Energy Administration)

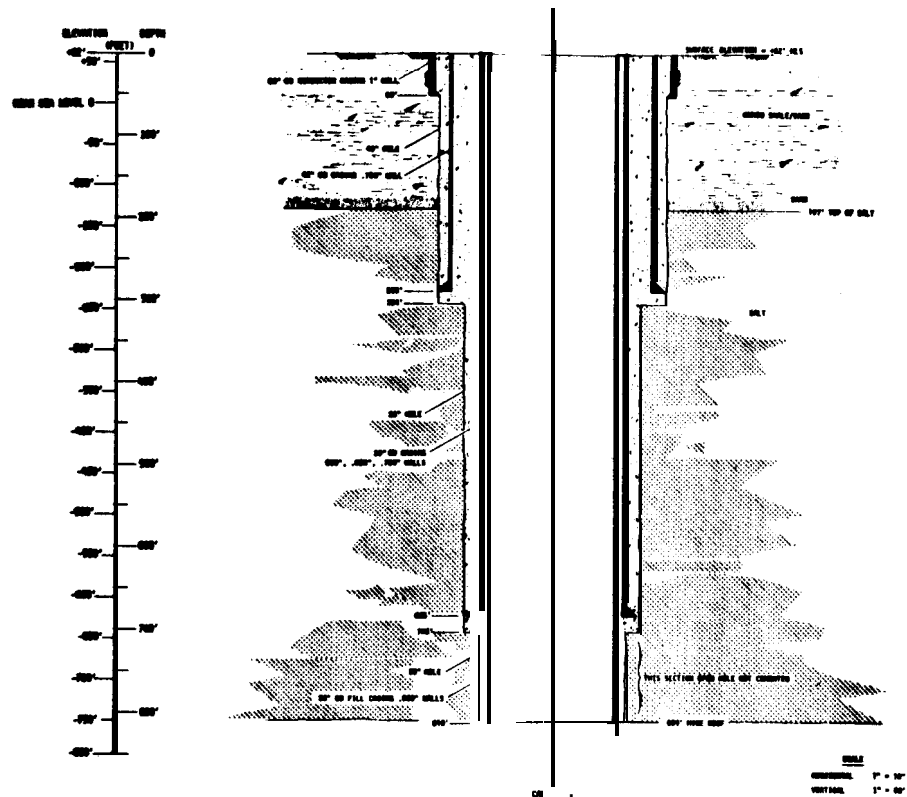


Figure 4 - FILL HOLE NO. 1 (From Fenix & Scisson, Inc., As-Built Completion Report-Fill Hole No. 1; West Fill Hole - Weeks Island Complex - Strategic Petroleum Reserve, prepared for Parsons-Gilbane under subcontract No. 286-1080-000 to the U. S. Department of Energy Strategic Petroleum Reserve Program)

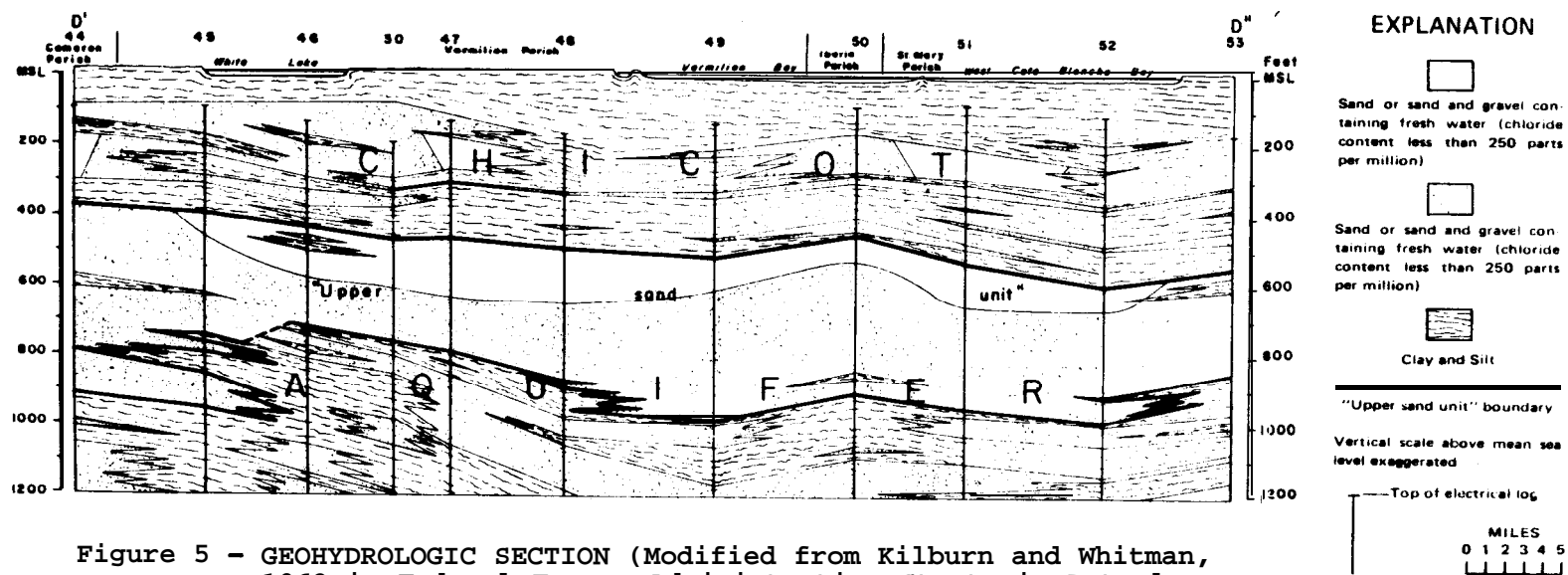
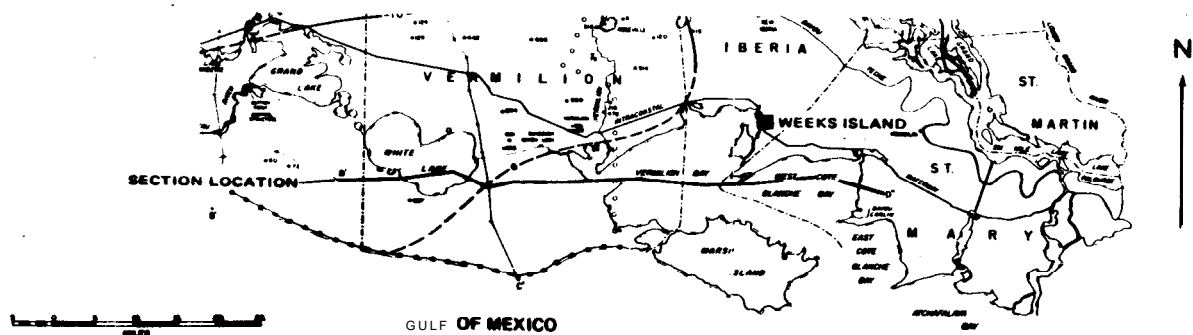


Figure 5 - GEOHYDROLOGIC SECTION (Modified from Kilburn and Whitman, 1962 in Federal Energy Administration Strategic Petroleum Reserve Office, 1976, Draft Environmental Impact Statement for Weeks Island Mine)

Salt Dome

Dome Geometry - Morton Salt Company has provided a contour map of Weeks Island that was compiled from seismographic and well data. The dome is slightly less than two miles in diameter at the 800-foot contour and approximately **2-1/4** miles at the **10,000-foot** contour (Fig. 6). The top is flat with few known pinnacles (Fig. 7). The dome is vertical to overhung on the north and east flanks and dips 60-80 degrees on the south and west flanks. According to Kupfer⁴, (a consultant retained by Gulf Interstate Engineering Company) the salt extends down at least 15,000 feet below the surface. Domal shale or sheath encircles the dome below 12,000 feet except on the west flank where it is at 9000 feet (Fig. 8).

Hydrocarbons - Oil is produced on the flanks of the Weeks Island dome. Major oil accumulations are present on the north flank where oil is trapped by the overhang. Morton Salt Company retains rights to the oil and gas in the salt itself thereby prohibiting drilling into it.

Brine Wells - Two brine wells drilled originally to 1,897 feet and 1,598 feet are located 1400 feet northeast of the oil storage area (Fig. 6). Currently, Morton Salt Company is producing brine only from Brine well #1, the well farthest from the oil storage area. The closest well has been sonar surveyed and poses no threat to the oil storage area¹².

Exploratory Drill Holes - Morton Salt Company and the previous owner of the mine, Myles Salt, drilled holes to define the top of the salt. Only two penetrated the salt to great depth. One of the holes, #16, 100 feet south of the mine, was drilled to 745 feet. The other, X84 2600 feet northwest of the mine, was drilled to 801 feet (Fig. 6). It is not known if these holes have been sealed². Exploratory borings were also drilled from within the lower level mine to investigate salt quality ahead of the working faces (Fig. 9). Five known holes were drilled approximately 300' vertically from the floor.

Mine Geology - The mine has been worked at two levels by the room and pillar method (Fig. 7). Production from the first level (-535 MSL) began in 1902. Production from the second level (-735 MSL) began in 1955 when the first level was abandoned. Pillars of the second level are nearly directly under the pillars of the first level. As mining extended to the east of the upper level, the room width increased from 50 to 70 feet with pillars remaining 100 feet in length and width throughout. Room heights are approximately 75 feet. Minimum distance from the edge of the dome to the oil storage area is greater than 1100 feet.

Shear Zones - Not all salt in a salt dome moves at the same rate. Differential movement causes shearing. Three shear zones have been defined at Weeks Island by Kupfer² (Fig. 10). The most severe is on the northeast boundary of the lower level in Rooms G-Z. Another

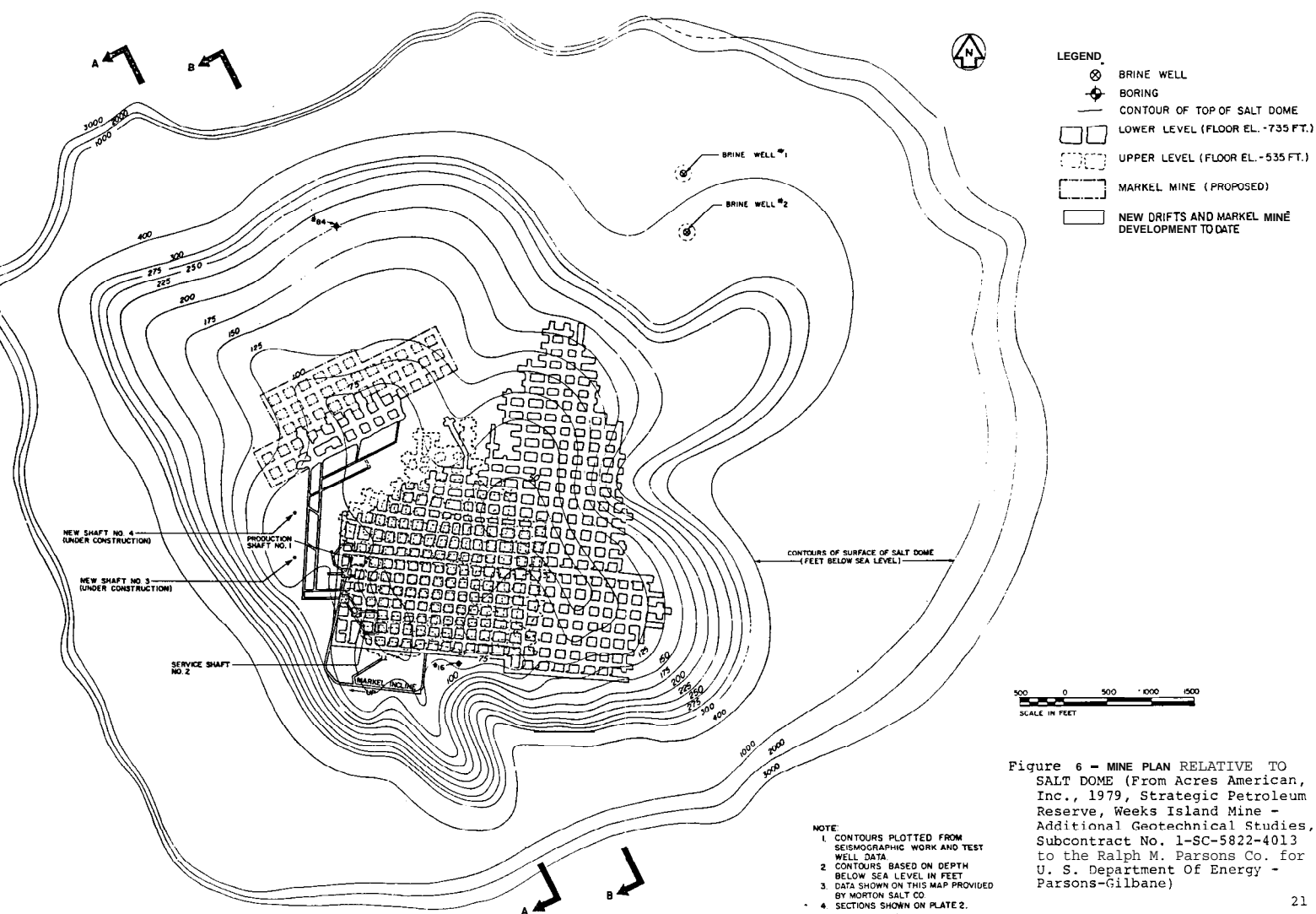
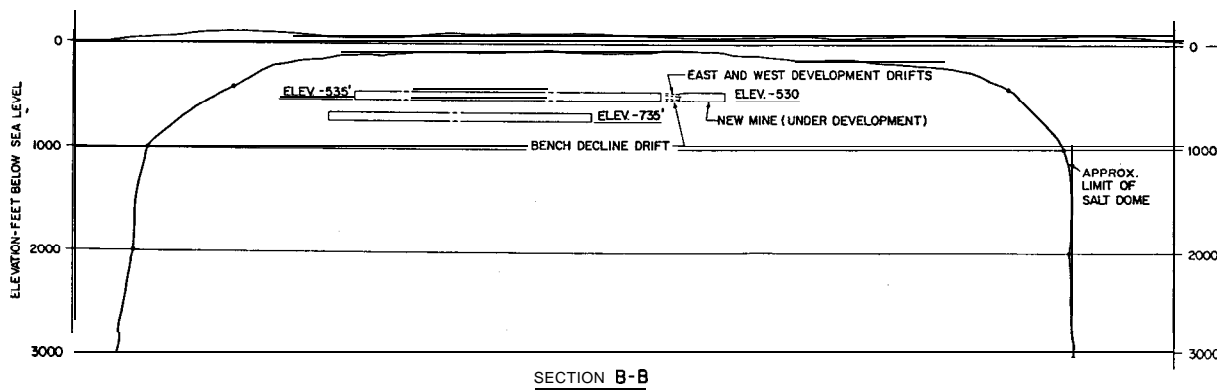
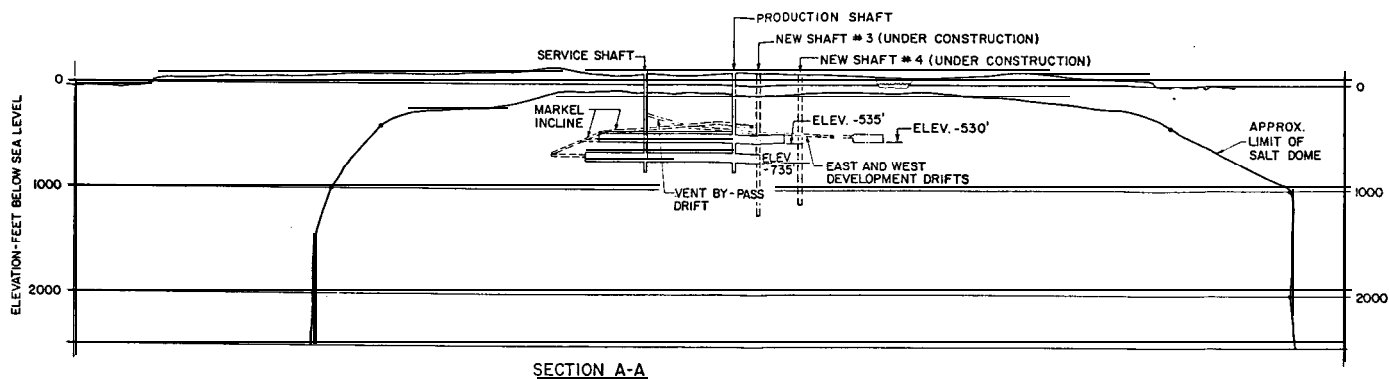


Figure 6 - MINE PLAN RELATIVE TO SALT DOME (From Acres American, Inc., 1979, Strategic Petroleum Reserve, Weeks Island Mine - Additional Geotechnical Studies, Subcontract No. 1-SC-5822-4013 to the Ralph M. Parsons Co. for U. S. Department Of Energy - Parsons-Gilbane)



500 0 500 1000 1500
SCALE IN FEET

SEE PLATE I FOR
SECTION LOCATIONS.

Figure 7 - CROSS SECTIONS THROUGH SALT DOME AND MINED AREAS (From Acres American, Inc., 1979, Strategic Petroleum Reserve - Weeks Island Mine - Additional Geotechnical Studies, Subcontract No. 1-SC-5822-4013 to the Ralph M. Parsons Co. for the U. S. Department of Energy - Parsons Gilbane)

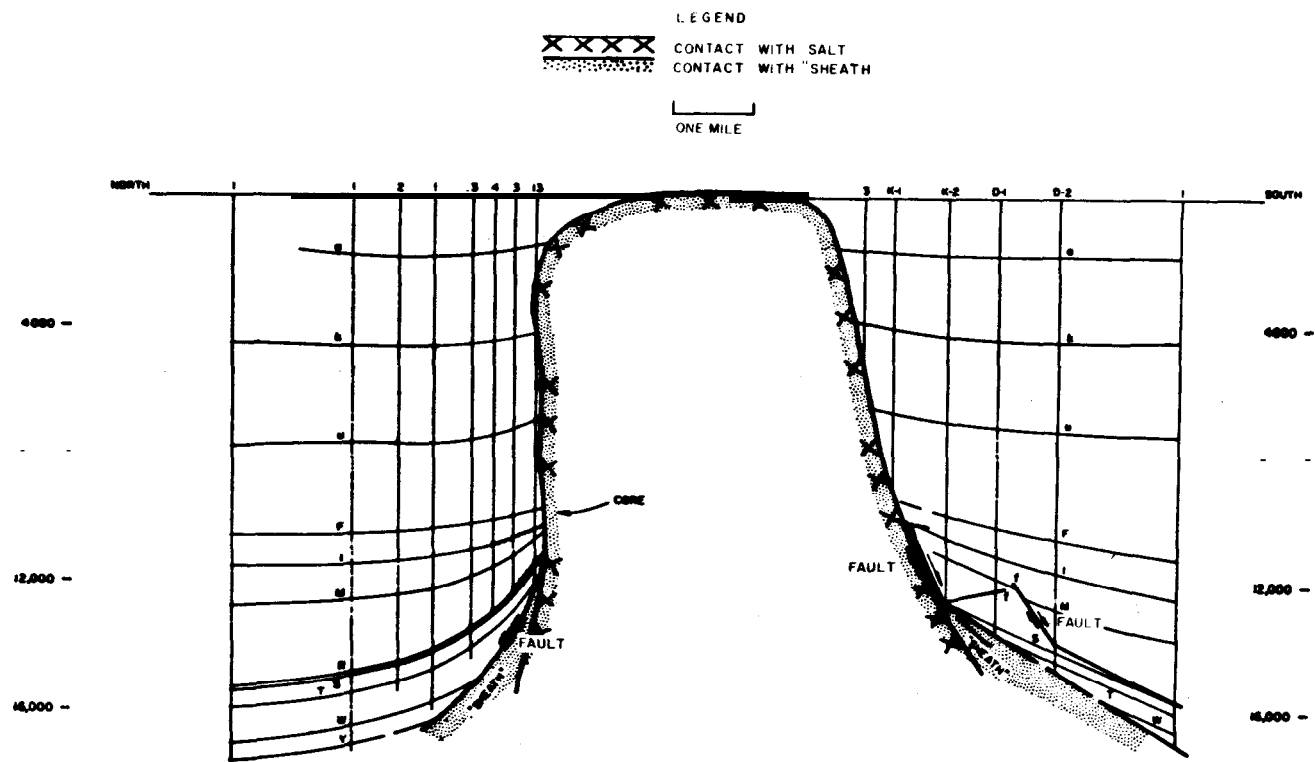


Figure 8 - CROSS SECTION OF WEEKS ISLAND SALT DOME (Modified from Johnson and Bredeson, 1971, in Federal Energy Administration Strategic Petroleum Reserve Office, 1976, Draft Environmental Impact Statement for Weeks Island Mine)

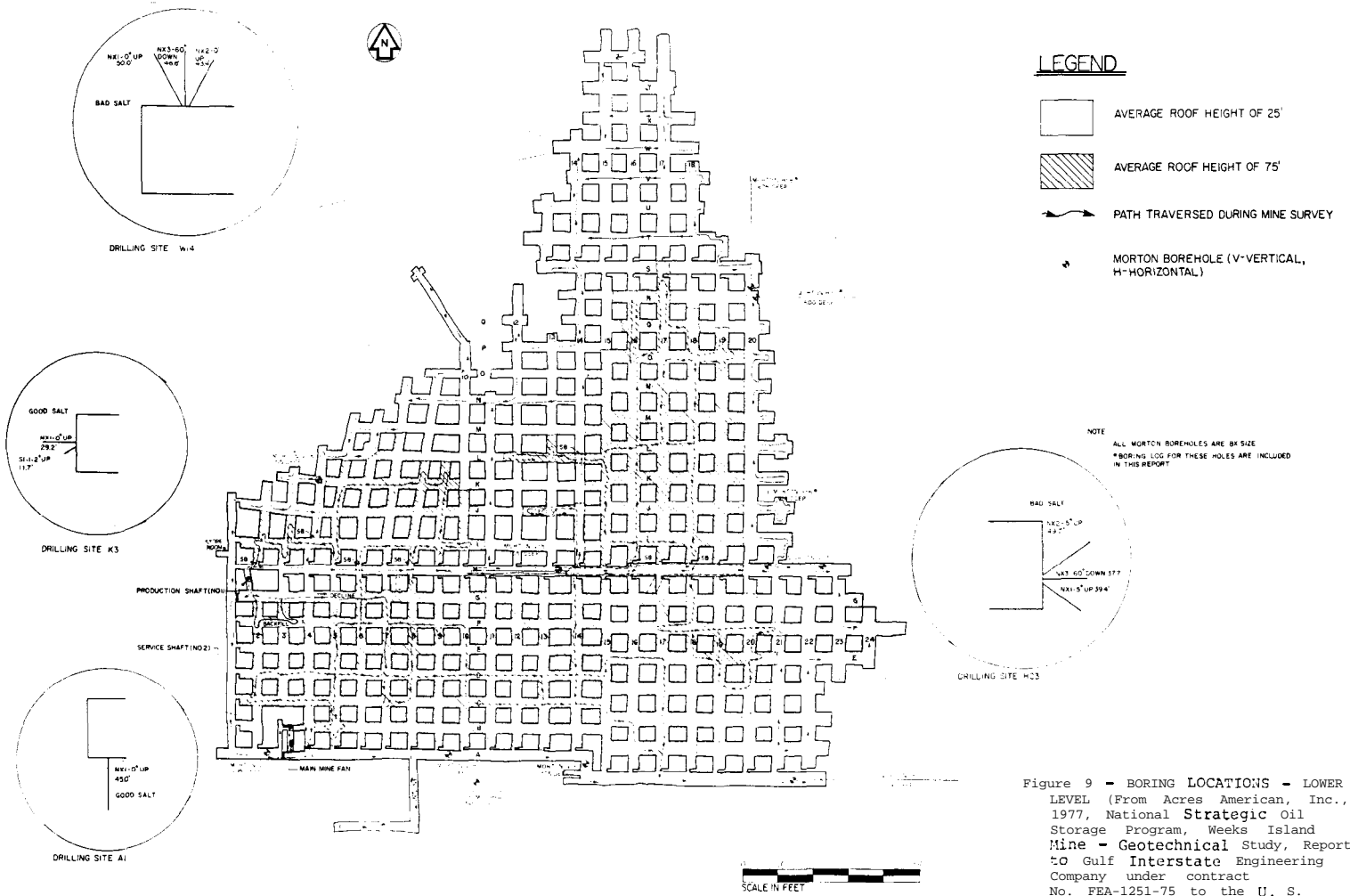
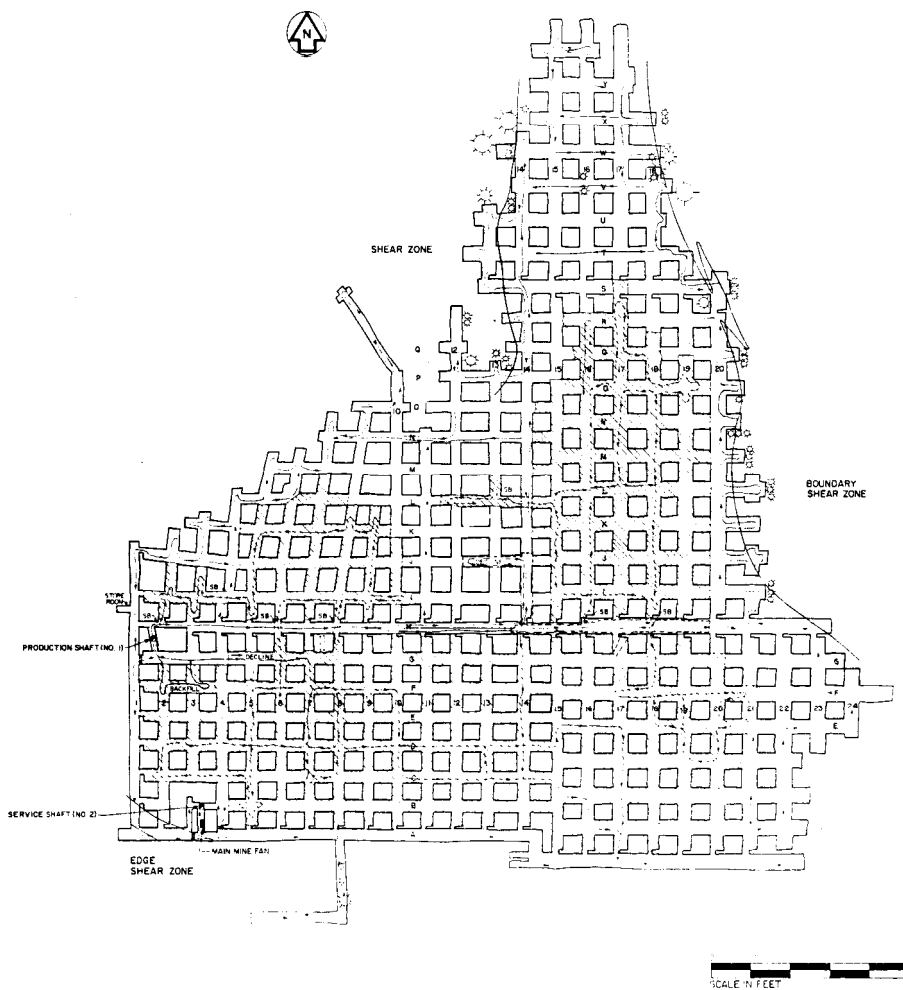









Figure 9 - BORING LOCATIONS - LOWER LEVEL (From Acres American, Inc., 1977, National Strategic Oil Storage Program, Weeks Island Mine - Geotechnical Study, Report to Gulf Interstate Engineering Company under contract No. FEA-1251-75 to the U. S. Federal Energy Administration)



LEGEND

-  AVERAGE ROOM HEIGHT OF 25'
-  AVERAGE ROOM HEIGHT OF 75'
-  PATH TRAVERSED DURING MINE SURVEY
-  BOUNDARY OF SHEAR ZONE
-  BLOWOUTS APPROX. 20'-40' IN DIA.
-  BLOWOUTS APPROX. 10'-20' IN DIA.
-  BLOWOUTS OR BOOTLEGS UNDER 10' DIA.

NOTE
LOCATION OF SHEAR ZONES AND BLOWOUTS BASED ON
MAPPING BY DR. DONALD KUPFER AND ACRES AMERICAN INC.

Figure 10 - SHEAR ZONES AND BLOWOUTS -
LOWER LEVEL (From Acres American,
Inc., 1977, National Strategic
Oil Storage Program, Weeks Island
Mine - Geotechnical Study, Report
To Gulf Interstate Engineering
Company under contract No.
FEA-1251-75 to the U. S. Federal
Energy Administration)

shear zone is in the northwest of the lower level in Rooms M-Z. The third shear zone identified by Kupfer is in the southwest corner of the lower level but the zone was not substantiated by Acres². Acres² tested the shear zones and found them to be impervious and competent.

Banding and Folding - On fresh faces and ceilings, 2 to 8 inch halite layers alternating with thin dark layers containing anhydrite inclusions are visible. No bands of pure anhydrite exist. The salt is banded and intensely folded in some areas due to the vertical emplacement of the salt. Banding and folding are more intense in "shear zones" where two spines of salt have moved **together** differentially. Walls often show near vertical banding⁶.

Leaks - Minor gas seeps are fairly common in the mine, lasting a few days to years and occurring in all types of salt. The seeps are a **local** phenomena which will not adversely affect the integrity of the mine². Gas trapped in crystals and along crystal boundaries is released during blasting.

Brine and oil leaks are random and fairly common in the mine. Areas generally drip brine for only a few days or months, forming rust-brown stalactites characteristic of the high iron content of connate waters. It is generally believed that these leaks are from trapped connate waters in the salt mass. Petroleum leaks dry up in a few years rather than months, probably because of the greater viscosity of the oil.

Blowouts - Blowouts, or outbursts, are conical openings which occur during blasting. The largest at Weeks Island is about 30 feet in maximum direction (Fig. 10). Blowouts are associated with ceiling slabbing, orange sandstone, yellow salt, jointed salt, black salt, clay and large open folds.

Blowouts result from the release of local entrapped gas. They are expected to occur when the effective pore pressure minus the stress **induced** pressure reaches a critical value for the salt. Mining causes a sudden reduction of the stress related pressure in the **salt** making blowouts possible if gas is present. Dames & Moore⁶ investigated blowouts and concluded that no single geologic characteristic allows prediction of blowouts, but precautions in mining can reduce their possibility. Acres² examined areas of blowouts at Weeks Island and found no sign of structural weakness.

Properties of the Salt

In 1977 Acres and their subcontractor **RE/SPEC**, conducted an in-mine investigation of both levels of the mine, the service shaft and the production shaft. Core drilling at four sites in the lower level, and field and laboratory testing was carried out. The

drilling extended up to 50 feet into the walls of the mine. Core samples were recovered for laboratory testing and permeability tests were conducted in the drill holes to assess the in situ permeability of the salt. Laboratory testing included chemical analysis, uniaxial and triaxial strength tests, permeability tests (to nitrogen and fuel oil), reactivity between salt and crude oil and simulated recovery tests from loose granular salt. Laboratory testing was done by Core Laboratories, Terra Tek, Dr. Thomas Usselman of the State University of New York in Buffalo and in Acres and **RE/SPEC's** laboratories. **RE/SPEC** also conducted mathematical analyses. Dr. D. H. Kupfer assisted with the geology, and Dr. Clay D. Durham, Jr. was retained as a geological consultant.

In 1979 Acres conducted an additional study of the mine. Acres drilled and sampled the first level salt to confirm that the salt characteristics are essentially uniform throughout the oil storage area. In-mine investigations included drilling and sampling at five sites. A total of 11 holes were drilled up to 40 feet into the salt. In-situ permeability testing was carried out in all drill holes using both nitrogen and diesel fuel as test fluid. Samples recovered from the upper level were laboratory tested to determine shear strength and permeability characteristics. Petrographic and spectrographic analyses were conducted. All drifts and mining areas excavated since the earlier investigations were closely inspected, particularly various bulkhead locations and areas where water seepage had occurred. Acres concluded that none of the work had adversely affected the oil storage area.

Details of testing procedures and equipment used as well as complete results can be found in the geotechnical reports by Acres of 1977 and 1979. Laboratory tests were done by Soil Testing Engineers, Inc.; Delta Testing & Inspection, Inc.; Core Laboratories, Inc.; Terra Tek; James Murphy at the State University at Buffalo; and Acres Environmental Laboratories.

Petrographic Analysis - The salt was analyzed petrographically during **both** the 1977 and the 1979 geotechnical study. The salt, in general, shows a strong fabric which is principally defined by elongation and only secondarily by flattening of grains. The fabric is roughly vertical. Grain boundaries are flat or curvilinear, not irregular or sutured. Grain size and shape varies from site to site, but individual samples are uniform. Salt crystals are $1/8$ to $1/2$ inches in diameter. Most samples are friable, possibly because of the lack of small grains dispersed between the larger grains.

The **salt** is unusually pure. Impurities (except in shear zones) are 99% anhydrite. Darkness of the salt is often due to internal reflection in colorless crystals rather than to impurities. Other inclusions include clays, hydrogen sulfide, carbon dioxide, and petroleum products. Lenses of sandstone and marly clays caught up during movement of the salt are common in shear zones.

Anhydrite is a constant accessory (1% to 2%). Anhydrite grains are contained entirely within individual salt grains. Liquid and gas inclusions occur along cleavages and preexisting fractures or grain boundaries. Grain boundaries are commonly lined with vugs, resulting in the porosity of 1% to 5%.

Spectrographic Analysis - The results of the spectrographic analysis of the salt of both levels are similar. Salt from the **upper** level is 98.9% pure with chief impurities being Ca, S, K, Al, **Fe**, Si, and Sn in order of decreasing concentrations. Samples from the lower level contained slightly more impurities including Ca, P, K, Si, Al, Fe, and Sr in order of decreasing concentrations. However, for practical purposes, no major variations between levels were noted³.

Unconfined Compression Tests - The unconfined compressive strengths of salt obtained from the upper level are comparable to the highest strength obtained from four cores from the lower level. Samples from the upper level were handled with great care during transportation to avoid in-transit disturbance. The results of the 1979 tests of the upper level salt are more consistent than results of the lower level salt tests probably due to greater care in sample handling. The differences between the two test series are not considered significant and do not indicate any major variation between the two locations⁴. An average unconfined compressive strength of 2500 psi, the average of the 1979 tests less one standard deviation, is considered applicable to the salt of both levels of the mine.

Triaxial Compression Tests - Triaxial compression tests of the salt were run at 0, 500, and 1000 psi. Results, including the unconfined strength value of 2500 psi, were plotted on Mohr circle diagrams. There are significant variations in strengths of the salt from various sites at Weeks Island. The strength of the salt in the upper level is lower than that determined for the lower level. The major difference is an apparently lower friction angle combined with a higher cohesion intercept. To compare results from different sites of the upper level, all the Mohr stress circles were plotted on a single figure (Fig. 11j). A recommended lower limit parabolic envelope for the upper level results is indicated. At 500 psi normal stress, the failure shear stress for the lower level envelope is 1060 psi, while the upper level is 960 psi - some 10% lower. At lower normal stresses, the differences decrease and, in fact, the series indicates higher strengths at normal stresses less than 350 psi, which is appropriate for the upper **level**³.

In summary, salt samples from the upper level exhibit lower strength and modulus of elasticity and higher unconfined strengths compared with salt from the lower level. The latter may be due to more careful sampling, handling and testing³,

Tensile Strength Tests - Tensile strength of salt from the upper level is significantly less than that of salt from the lower level, probably due to sample preparation. During the Brazilian tests,

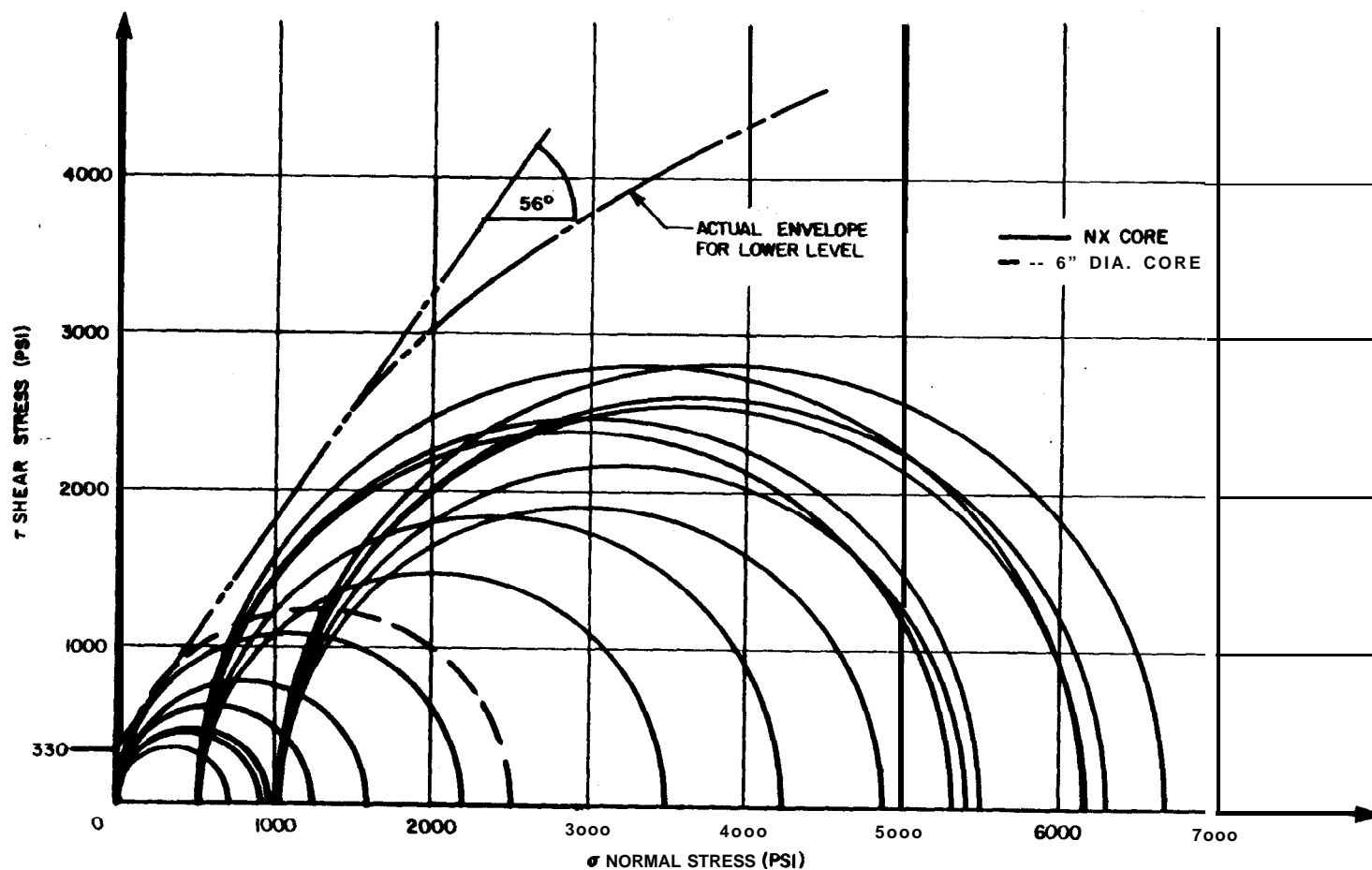


Figure 11 - MOHR STRESS CIRCLES - ALL SITES - UPPER LEVEL
 (From Acres American, Inc., 1979, Strategic
 Petroleum Reserve - Weeks Island Mine - Additional
 Geotechnical Studies, Subcontract No. 1-SC-5822-4013
 to the Ralph M. Parsons Co. for U. S. Department of
 Energy - Parsons-Gilbane)

sample crumbling was the observed failure mode. There was no indication of any cross-grain tensile fracturing. Grain boundary failure was the dominant mode in the small samples used. Test results are not considered truly representative of the in situ strength of the salt and were not used in the Mohr circle calculations.

Creep - Morton Salt measured horizontal and vertical creep using convergence rods located in the salt in the ore room of the lower level from 1961-1967. Convergence of salt varies but is approximately 1/2 inch per year. Because of lack of additional data, these measurements cannot be extrapolated to other parts of the mine. The convergence should be slightly less when the mine is filled with oil. Nevertheless, pressure should be monitored in the mine since a decrease in total volume will increase vapor pressure above the oil.

Permeability Tests - Permeability tests were run in-situ and in the laboratory. In-situ tests indicate that salt in the upper and lower levels has a permeability of less than 0.02 millidarcys. Laboratory test results of 1979 indicate a decrease of permeability with increasing confining pressure. The final measured permeability under a pressure of 100 psi ranged between 1.5 and 6 millidarcys for diesel fuel, and between 1.3 and 14 millidarcys for air. The 1977 tests indicated permeabilities of 0.3 to 12 millidarcys for diesel fuel and 1.3 to 20 millidarcys for nitrogen. Since it is highly probable that some stress relief occurred following drilling and transport to the laboratory, in situ results are considered to be more reliable³ than laboratory results (Fig. 12).

Salt/Oil Reactivity - Five salt samples were crushed and submitted to salt/oil reactivity testing. Both pure and impure salt was used. The tests show little chemical reactivity between crude oil and salt. No absorption of the oil into the salt crystals was observed, nor was there any evidence of any rock failure due to swelling or disintegration of the samples.

Condition of the Oil Storage Area

Effects of Mining - Mining processes have caused jointing and disaggregation up to 20 feet back from the mining surface. Slabbing is common on the older surfaces².

Natural adhesion of the oil to salt and the increased porosity due to the friable surfaces, jointing and slabbing as well as loose salt debris left on mine floors will reduce oil recovery. Acres² conducted oil withdrawal tests from loose salt and found that a minimum oil loss of 0.4 percent of the total volume of oil would be lost in unremoved salt piles. However, losses of oil will occur in the first fill/withdrawal cycle only.

Mine conversion work included scaling off loose slabs of salt from pillars and walls. and grading the loose salt piles to ensure free flow of oil.

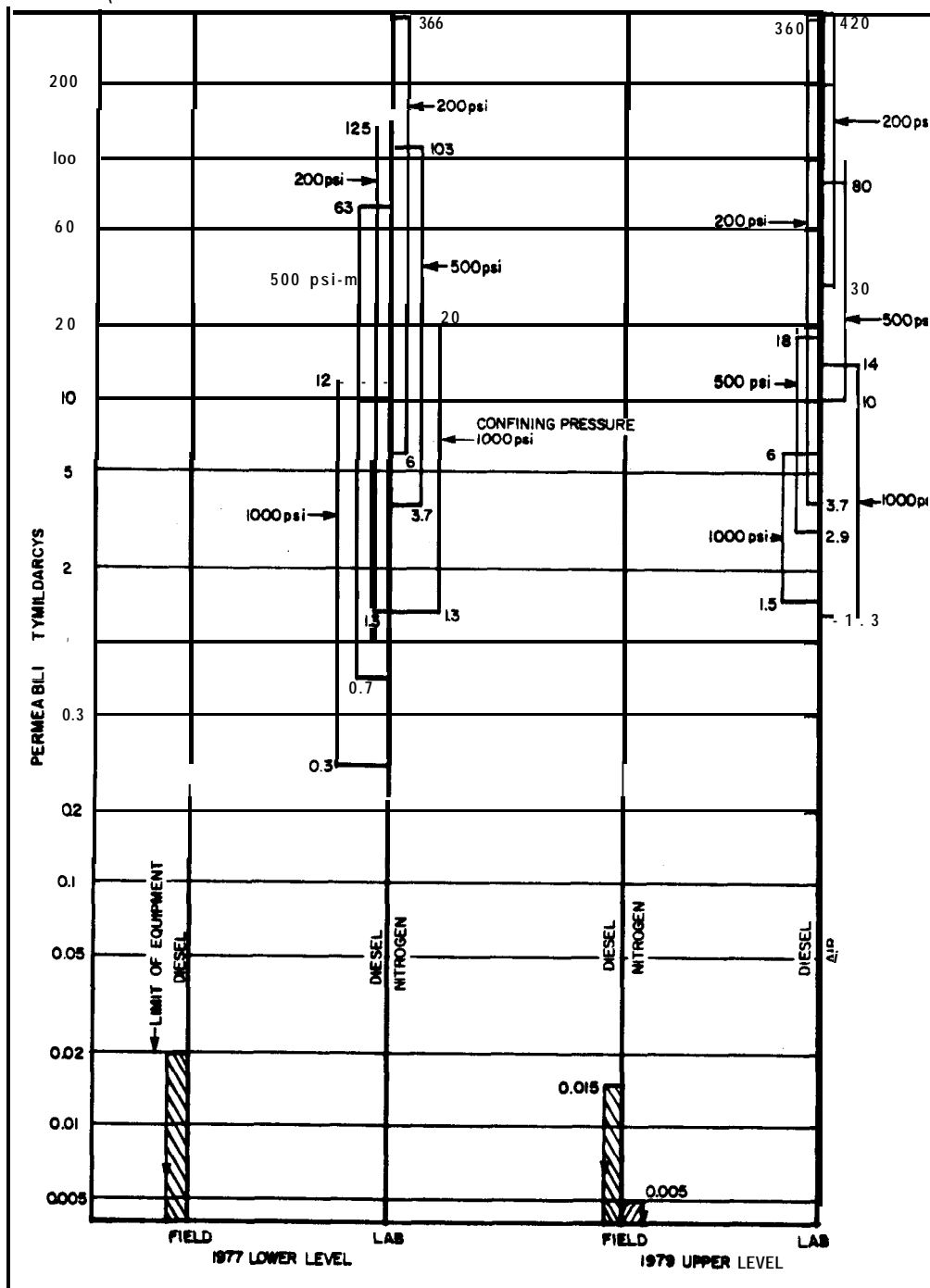


Figure 12 - COMPARISON OF FIELD AND LABORATORY PERMEABILITY TEST RESULTS - UPPER AND LOWER LEVELS (From Acres American, Inc., 1979, Strategic Petroleum Reserve - Weeks Island Mine - Additional Geotechnical Studies, Subcontract No. 1-SC-5822-4013 to the Ralph M. Parsons Co. for U. S. Dept. of Energy - Parsons-Gilbane)

Pillar Stability - The 1977 Acres in-mine survey revealed extensive pillar decay due to spalling and ravelling throughout both levels of the mine. In many areas large slabs were separated from the pillars. Pillar decay is essentially a result of rupture which occurs under both elastic deformation (brittle failure) and time dependent deformation (creep rupture). Analyses of pillar strength were made by both the tributary theory, assuming a uniform compressive stress across a pillar, and by the finite element method to show the distribution of the principal stresses throughout pillar and adjacent salt mass. The pillars will remain stable^{2,3}.

Mine Roof Stability - The mine roof in general shows no sign of failure. Blowouts in the roof do not appear to affect overall roof stability*. Mine conversion work, which included scaling loose slabs on pillars, did not affect roof stability. Drilling holes between the two levels, tunneling into the service shaft sump and removal of salt bridges along room H also appeared to have no adverse affect on the stability of the mine pillars or roof³. The comparable strengths of the two levels and absence of any signs of distress in the roof implies that there is little risk of collapse other than minor roof falls or spalling in either level and that such falls would not adversely affect the overall stability of the mine or lead to loss of oil³.

Shafts - Two shafts serve the oil storage area (Fig. 13). The service shaft, 9 feet in diameter, was built from 1898 to 1902. The shaft extends 784 feet below sea level to the lower level. The shaft is lined approximately 40 feet into the salt.* Effectiveness of seals and condition of concrete are unknown. Acres suggested installation of pressure taps to monitor water pressure behind the shaft. No serious problems in the service shaft have occurred to date. The shaft is not plumb, however, and Morton did experience occasional jamming of the cage in the guides indicating some ongoing movement of the shaft³. The service shaft holds the lines and pumps that will be used for oil recovery. The manifold room is located in the service shaft. Acres² notes that there could be serious potential for damage to the oil recovery equipment because of flooding or failure of the shaft. An alternate withdrawal system through the fill holes is possible.

The production shaft was constructed in 1954 to 1955. It is 18 feet in diameter to a depth of 804 feet below sea level. The shaft is lined to 271 feet below the surface, 110 feet into the salt. Minor leaks have occurred in the production shaft, but these leaks have been stopped by grouting.

*Reports on the depth to the top of the salt vary from -39 MSL in the service shaft construction schematic to -57 MSL in the Acres 1979 report to -87 MSL in the Fenix and Scisson construction diagrams.

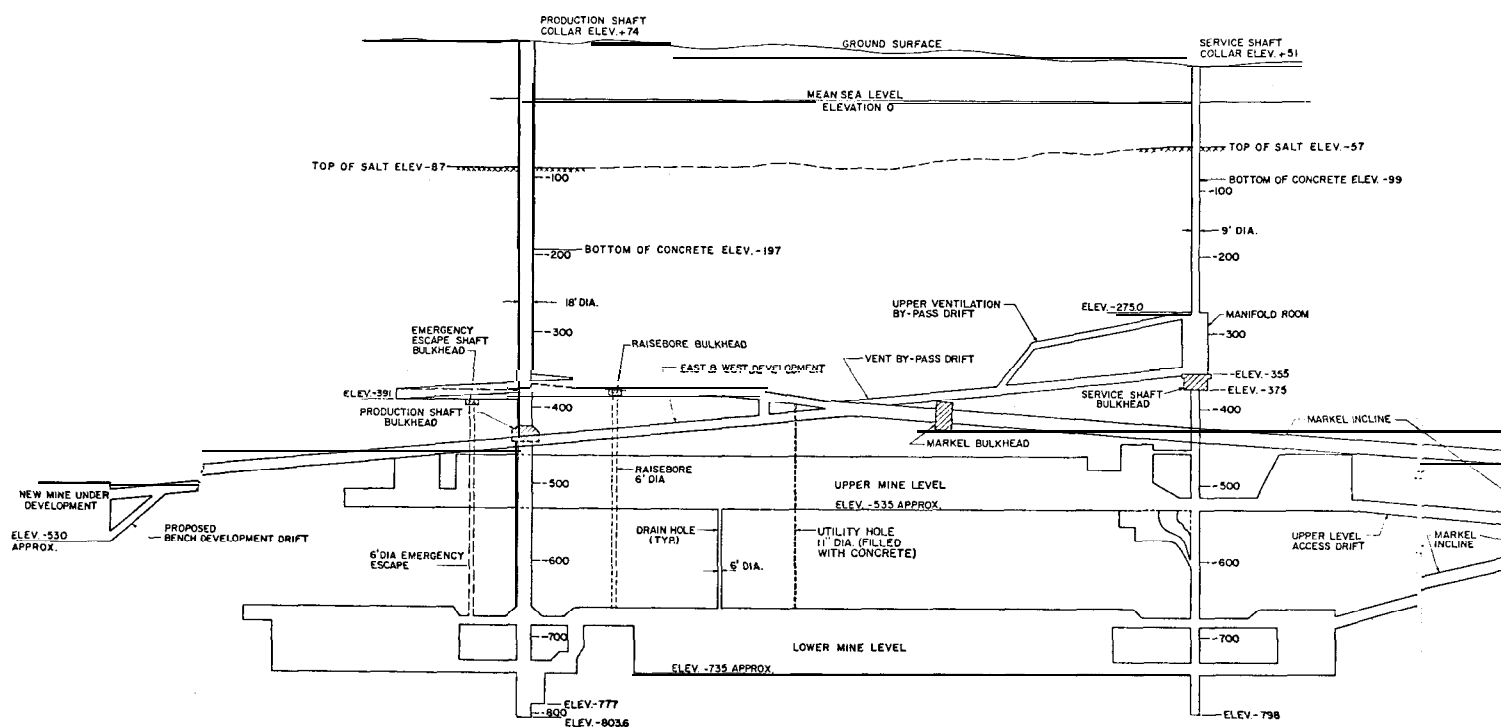


Figure 13 - SCHEMATIC SECTIONAL ELEVATION OF OIL STORAGE AREA, DRIFTS AND MARKEL MINE (From American, Inc., 1979, Strategic Petroleum Reserve - Weeks Island Mine - Additional Geotechnical Studies, Subcontract No. 1-SC-582 4013 to the Ralph M. Parsons Co. for U. S. Department of Energy - Parsons-Gilbane)

Drifts to the Production Shaft - Two drifts were excavated from the Markel Mine to the production shaft above the upper level (Fig. 14). One of the drifts is an extension of the Markel Incline and is now equipped with a salt delivery conveyor which carries the salt from the Markel Mine to loading hoppers serving the production shaft skips. Before installation of these hoppers, the salt from the Markel Mine was dropped to the lower level loading system through a six-foot diameter raisebore ore pass located at the end of a 100-foot spur drift³.

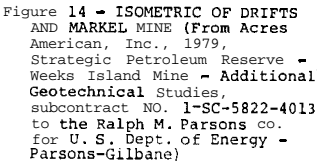
The other access drift to the production shaft circles the shaft and enters on the opposite side, below the first drift. Over room one of the lower level, another six-foot diameter raise was excavated to provide emergency escape during conversion of the lower section of the service shaft³. Both drifts were inspected in 1979 by Acres and found to be structurally sound with no indication of wetness.

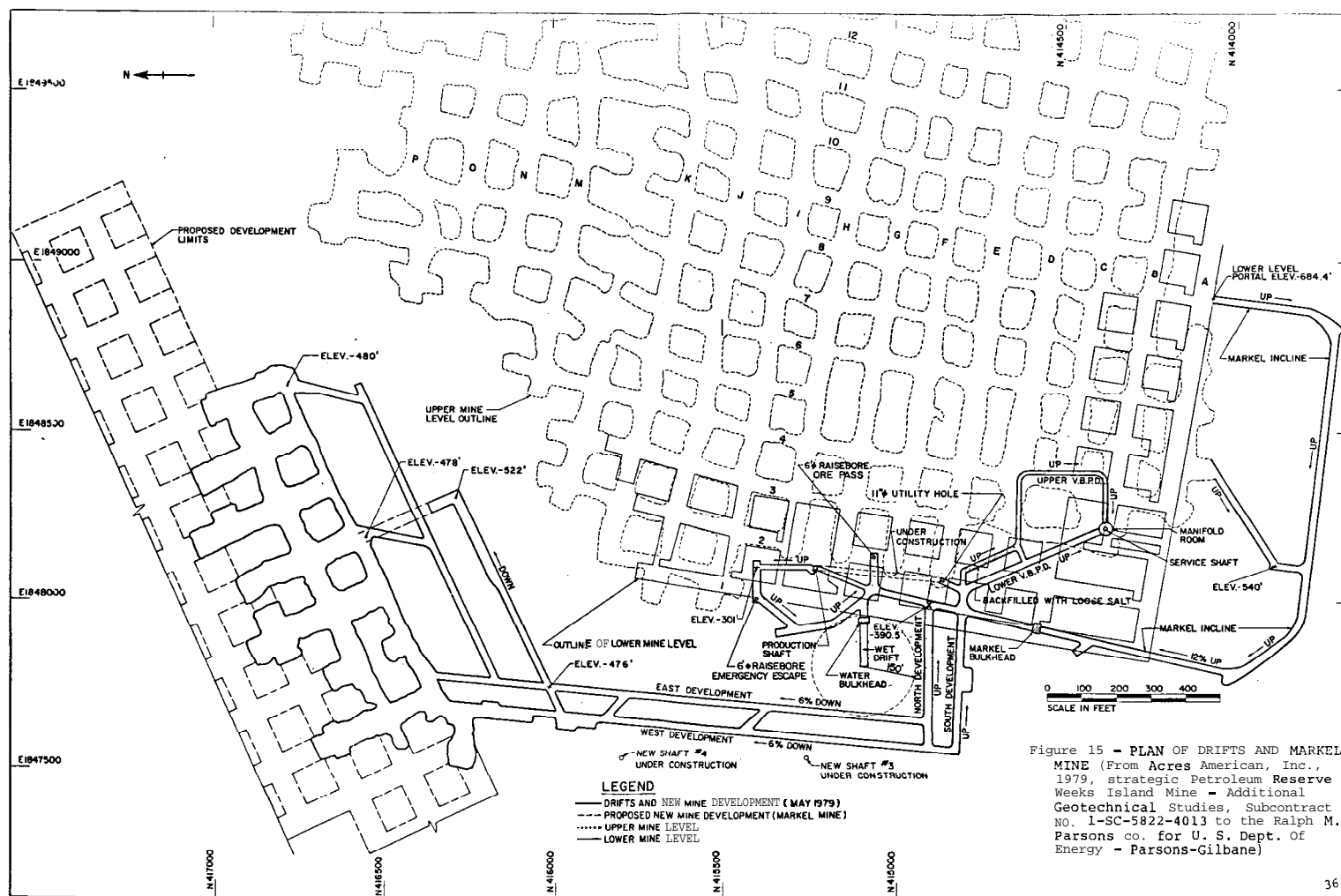
The two drifts were initially developed using normal drilling and blasting. However, during excavation, some water leakage occurred in the production shaft. The leaking area was grouted successfully, but to prevent further vibration, the excavation was completed using a mechanical miner³.

Drifts to the Service Shaft - The upper and lower ventilation bypass drifts were driven from the Markel mine to the service shaft (Fig. 14). The manifold room in the service shaft and the upper ventilation bypass drift, and the final 150 feet of the lower ventilation bypass drift were excavated with a mechanical miner. To carry utility lines during conversion, an 11-inch diameter hole was drilled at the end of a short spur drift from the lower drift to intersect the upper and lower mine level. Acres³ inspected the upper and lower ventilation bypass drifts and found them to be structurally sound with no sign of wetness. A short length parallel to the lower drift could not be inspected because it was backfilled with salt.

Bulkheads - The six direct connections between the Markel Mine and the oil storage area are 1) the service shaft/manifold room, 2) the production shaft, 3) the Markel Incline, 4) the six-foot diameter ore pass, 5) the six-foot diameter emergency escape, and 6) the 11-inch diameter utilities hole (grouted the entire length from the surface to the roof of the upper level). The connections were sealed in 1979 by concrete bulkheads (Fig. 15).

Prior to pouring the concrete, the salt was inspected by Acres. Acres found sound salt with no evidence of structural weakness or fissures. The **keyways** were excavated by use of a mechanical mining machine. Acres concluded that the salt will support the bulkheads throughout the life of the storage facility. The long-term stability and strength of the bulkheads themselves was not in Acres' scope of work.





Oil Containment - Permeability tests indicated mass permeabilities of less than 0.02 millidarcys. For all practical purposes the salt is impervious to oil and to hydrocarbon vapor and any other gases that may accumulate within the storage area. Inspection of the bulkhead **keyways** indicated sound **salt**³.

The history of mining at Weeks Island has generally shown that any seepage into the mine or structural weakness becomes apparent at the time of blasting. No water seepage into the oil storage area was observed by Acres in 1979. It is therefore reasonable to assume that leakage developing through the established perimeter of the mine will probably not occur unless the area is seriously disturbed by other mining in the dome.

Interim Mine

Markel Incline - To maintain continuous salt production during mine conversion activities, Morton Salt Company developed a new mining area (Markel Mine) through a series of drifts excavated from the original workings. The Markel Incline to the Markel Mine passes through the highly stressed areas of salt forming the perimeter pillar of the mine excavation through an area previously identified by **Kupfer**² as being a shear zone. One blowout occurred in the roof of the Markel Incline close to the lower level. Acres inspected the incline in 1979 and found no evidence of any structural weakness. A secondary tunnel from the lower level was also examined and found to be in good condition.

Wet Drift - In 1977, an area of wet salt was encountered during routine drilling and blasting of the planned access drift to the new Markel Mine (Fig. 15). Minor inflows of water occurred. Grouting substantially reduced the leakage but did not completely stop it. Test borings by Morton indicated a significant **zone** of wet salt around the wet drift, and it was decided to isolate the wet drift and excavate new access tunnels for the Markel Mine routed to clear the wet zone. The new tunnels were completed without any **difficulty**³.

In late 1978, during mine conversion work, the leakage rate in the wet drift increased. Grouting operations again did not completely stop the leak. To ensure the safety of the underground workings, a bulkhead was **constructed**. A steel pipe fitted with a watertight cover provides access to the area. If severe inflows were to occur, this drift could be sealed off and allowed to fill with brine without affecting other areas of the mine or the oil storage area³,

In March 1979, the leak rate was 1.6-2.0 gallons per hour. A grouting program is currently underway using chemical grout as in the past. Attempts at using cement grout when the leak first developed were unsuccessful. Dr. Joseph D. **Martinez**¹⁶, who studied the wet drift in detail, suggests that the proximity of the top of salt (282 feet) could have resulted in the intersection of

the drift with natural fissures extending downward, or with cracks generated by blasting and propagating upward to the top of salt, or a combination of both. Martinez feels that the leak is a result of mining too close to the top of the salt.

Markel Mine - The Markel Mine is located northwest of and at approximately the same depth as the upper level of the oil storage area (Fig. 14, 15). Access to the mine is through two interconnected drifts from the Markel Incline. At the closest point, the Markel Mine is 300 feet from the upper level of the oil storage area. Acres examined the access drifts and new mine workings in 1979. Particular attention was directed to the sections closest to the wet drift, but no signs of seepage were observed. Some areas of dampness, gas seeps and impure salt were noted in the Markel mine.

New Morton Mine

Design plans include a mine beneath the oil storage area. For that reason, several investigations of the safe web thickness between the two have been investigated. First in May 1977, the safe web thickness was investigated for Morton Salt by A. J. Henderson, Jr.¹⁴ of the University of Illinois using a finite element study.

In November of 1977, **Acres²** concluded an evaluation of a safe web thickness for the Federal Energy Administration also using a finite element model. Acres concluded that the storage of oil would have only a slight effect on the stability of the web and that a web of 300 feet would be adequate subject to qualifications regarding blowouts. The majority of the web will experience the same effective stresses regardless of the presence of oil. The slight increase in the effective stress near the lower level of the oil storage area will cause a slight variation in the deformation of the opening. The oil will in fact provide confinement to reduce pillar spalling in the storage area. Withdrawal of the oil will also have only slight effects. The oil storage area may experience accelerated creep for a short period of time, but it will be lower than after original excavation. Web thicknesses of 300 feet and 400 feet are practically identical in terms of stability although an increase in web thickness increases the region of undisturbed salt.

In August of 1978, the General Accounting Office (GAO) questioned the suitability of a mine beneath the oil storage area. GAO cited a report by the Mine Safety and Health Administration (MSHA). According to MSHA, even if only small blowouts were to occur, cracks and fractures resulting from the blowout could extend to the oil storage area with leaks resulting. In the report, MSHA concluded that no practical means exist to assure mining will not penetrate a blowout prone zone and that potential hazards are too great to permit mining 370 feet below oil storage. The report stated that unless facts were provided that assure a lesser distance is adequate, mining should not occur less than 650 feet below the oil storage area.

In a letter in Appendix I of the same GAO report, Morton Salt Company argues that if a blowout occurs in the oil storage area above, the horizontal stresses tend to seal the fractures. If a blowout occurs in the roof of the new mine below, the expelled salt would move out of the hole, and any cracks would parallel the remote end of the opening created, as evidenced by blowouts in salt and potash mines all over the world. Morton also notes that blowouts are related to relict bedding and that probe drilling is carried out routinely so that potential blowouts are bled off harmlessly.

In 1979, Sandia **Laboratories**^{18,19} performed finite element stress analyses for a single level mine model and for a two-level mine configuration with various vertical separations. Sandia concurred with the 300-foot safe web thickness proposed by Acres. The influence of blowouts was also addressed by Sandia. Stress analysis was performed for a two-level mine with a simulated outburst of 20 feet in radius and 150 feet in height occurring in the salt section between the oil storage area and a new mine planned below. The model blowout was significantly larger than any actual blowouts observed at Weeks Island mine. The conclusion was that the influence of blowouts is local and would not substantially reduce the integrity of the web. Calculations indicated that it is highly unlikely that a blowout in a new mining area would cause communication with the oil storage area. The existing mine surface is at a low initial pressure such that little additional relief in the vicinity of the existing mine can be created by ~~the~~ the new mining. To better predict the occurrence of blowouts, Sandia¹⁸ recommended laboratory efforts to measure the pressure difference level which causes blowouts in salt.

Morton has completed two new shafts to -1160 MSL and -1260 MSL to the west of the oil storage **area** (Fig. 16). The new shafts have no communication with the Markel Mine or the oil storage area. Morton will probably abandon the Markel Mine sometime in 1981 and start production at -1205 **MSL**. That level will not be mined under the oil storage area. A second level is planned 650 feet below the oil storage area (-1485 MSL) connected to the -1205 level by a decline. Current plans indicate that the -1485 level will not be mined for many years.

Natural Hazards

Flooding - Weeks Island is a local high area that will not be significantly threatened by flooding⁴. During the **100-year** storm, 100 foot waves could be generated in the open ocean. However, the waves that could be propagated inland across the marsh and bays to break along flooded island perimeters would be only 5 to 6 feet. The waves could not run up to elevations greater than 20 feet. The mine entrances are 50 feet above **sea** level.

Earthquakes - Weeks Island is in the low seismic risk zone No. 1 of the Uniform Building Codes. This section of the country **may** potentially experience minor damage, a V-VI on the Mercalli Scale. The most severe earthquake in the area was in 1930 **at** Donaldsonville, some 50 miles east of Weeks Island which **was** of

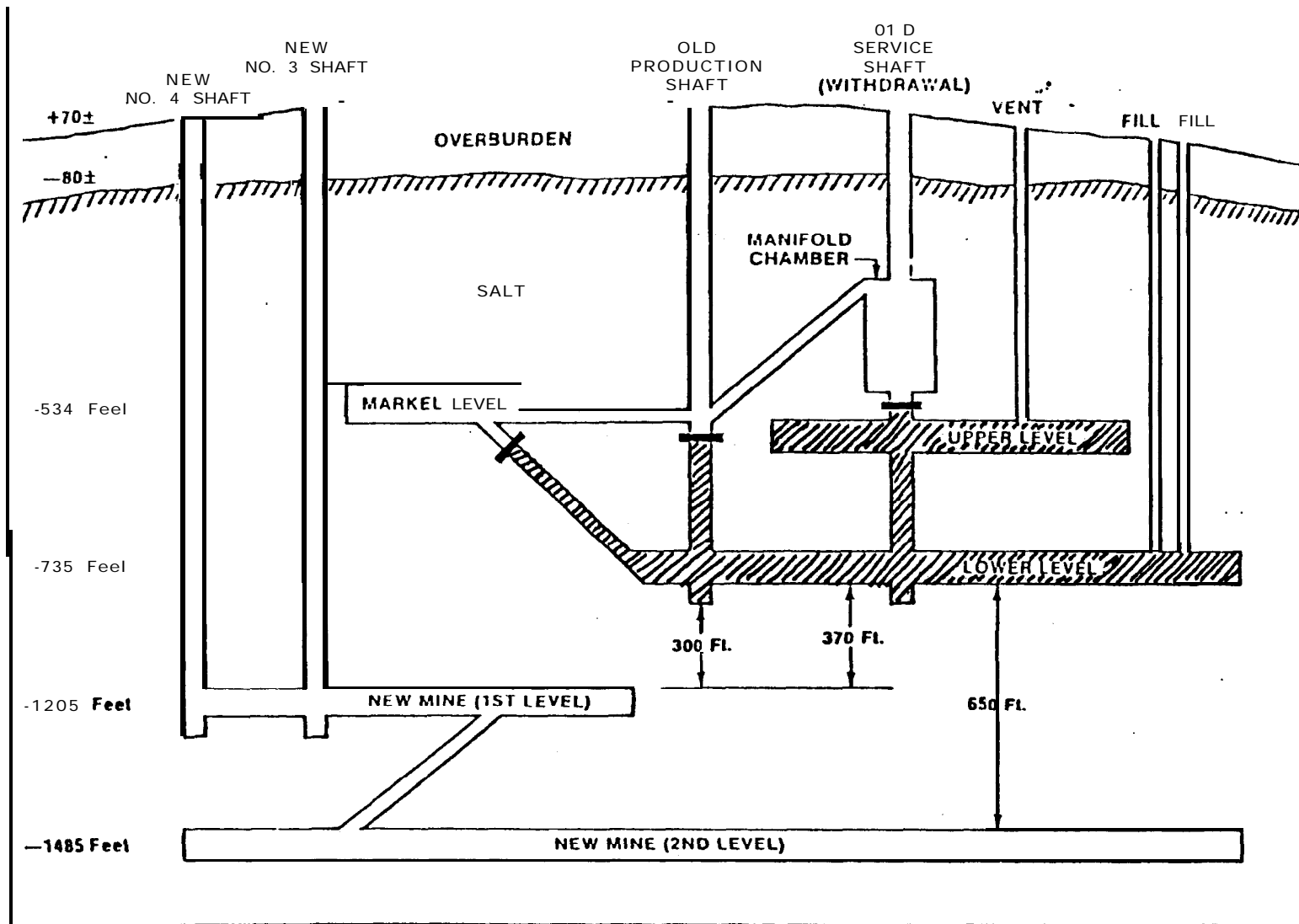


Figure 16 - SCHEMATIC OF OIL STORAGE AREA, MARKEL MINE AND PROPOSED NEW MINE LEVELS

intensity V-VI (Fig. 17). Minor damage resulted. An earthquake probably would not affect the oil storage area since underground facilities have additional support due to confinement. However, damage to shafts and oil recovery equipment could occur and there would be a possibility of a leak rate increase in the wet drift.

Current Status of the Oil Storage Area

DOE's property line extends approximately 300 feet laterally from the lower mine workings in all directions for a total area of 388 acres, and to 300 feet below the lowest point of the lower level of the mine.

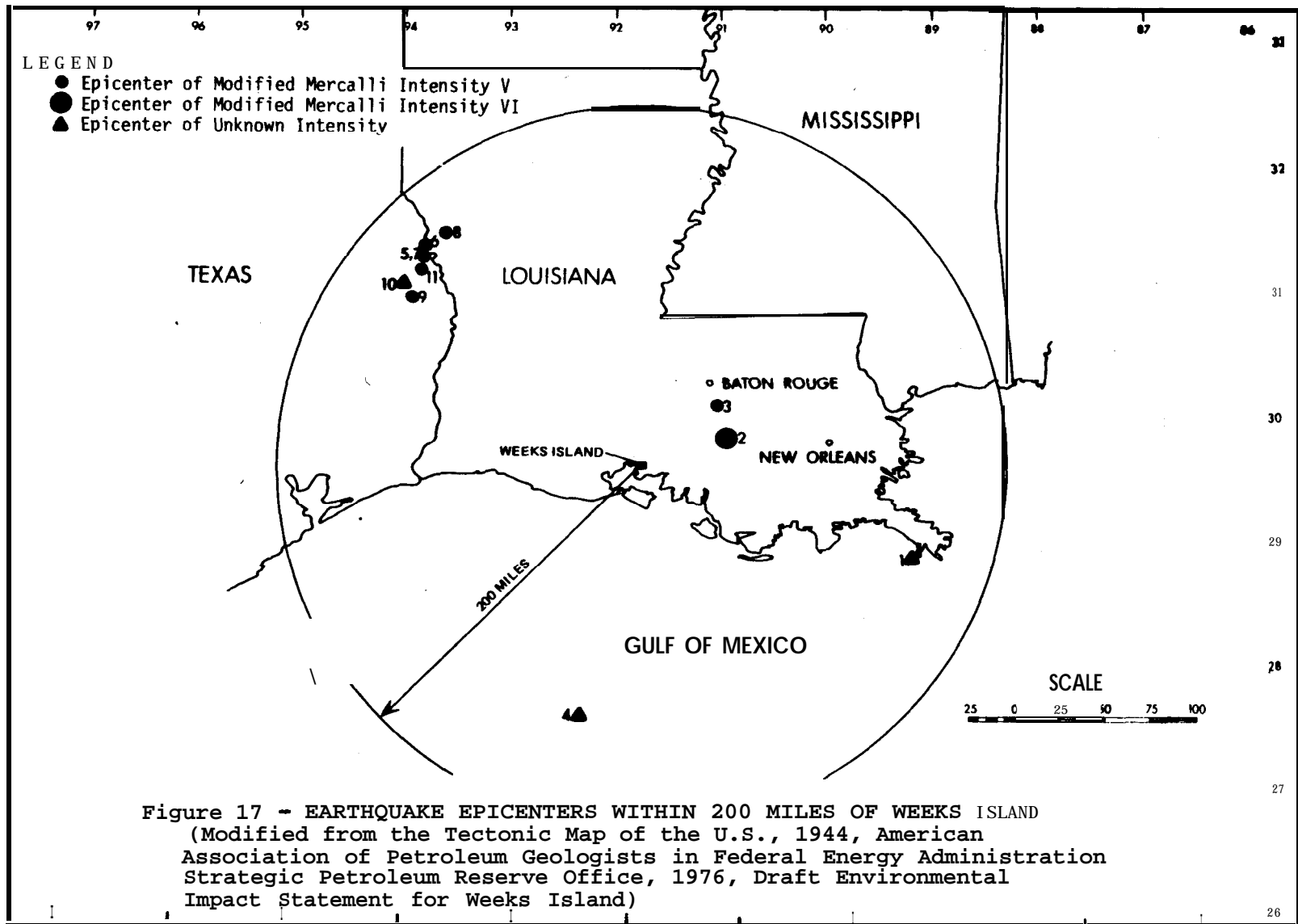
The DOE 1979 Annual Report states that the surface facilities at Weeks Island are 92% completed (Fig. 18). The mine conversion work and the Weeks Island-St. James pipeline are completed. The mine was filled with inert gas and ready for oil as of November 1979.

Mine conversion work included drilling of drainage shafts between the two levels of the oil storage area, tunneling into the service shaft sump, removal of salt bridges along room H, scaling of loose slabs from pillars and walls and grading loose piles of salt to ensure free flow of oil. The upper and lower ventilation bypass drifts were driven from the Markel Mine to the service shaft to aid in conversion of the service shaft to hold oil withdrawal equipment.

A static vent access **borehole** was drilled at the mainline pump station (Fig. 16). The hole is cased from the surface to the uppermost elevation of the mine. The surface elevation at the pump station is approximately **+95 MSL** and the top of salt is at **-102 msl**. A drilling activities log, a **borehole** geometry log and a cement bond log are included in a report by Fenix & Scisson⁹.

Two oil fill holes were also drilled and cased from the surface to the underground mine sump (809 and 810 feet below the surface). The surface elevation at the fill site is **+62 MSL** and top of salt is **-135 MSL**. Both the drilling activities log and a gyroscopic survey are available^{10,11}.

The oil piping distribution system consists of eleven (ten operational and one reserve) submersible electric pumps in the mine to boost oil to the surface and twin main line pumps (plus one reserve) to push the crude oil to St. James Terminal during drawdown. St. James Terminal is northeast of Weeks Island on the Mississippi River. Pumps total 17,000 horsepower. Weeks Island will be filled via a 36-inch diameter, 69 mile long pipeline from St. James Terminal at a maximum rate of 480,000 barrels per day. Total **drawdown** capability is 590,000 barrels per **day**²³.



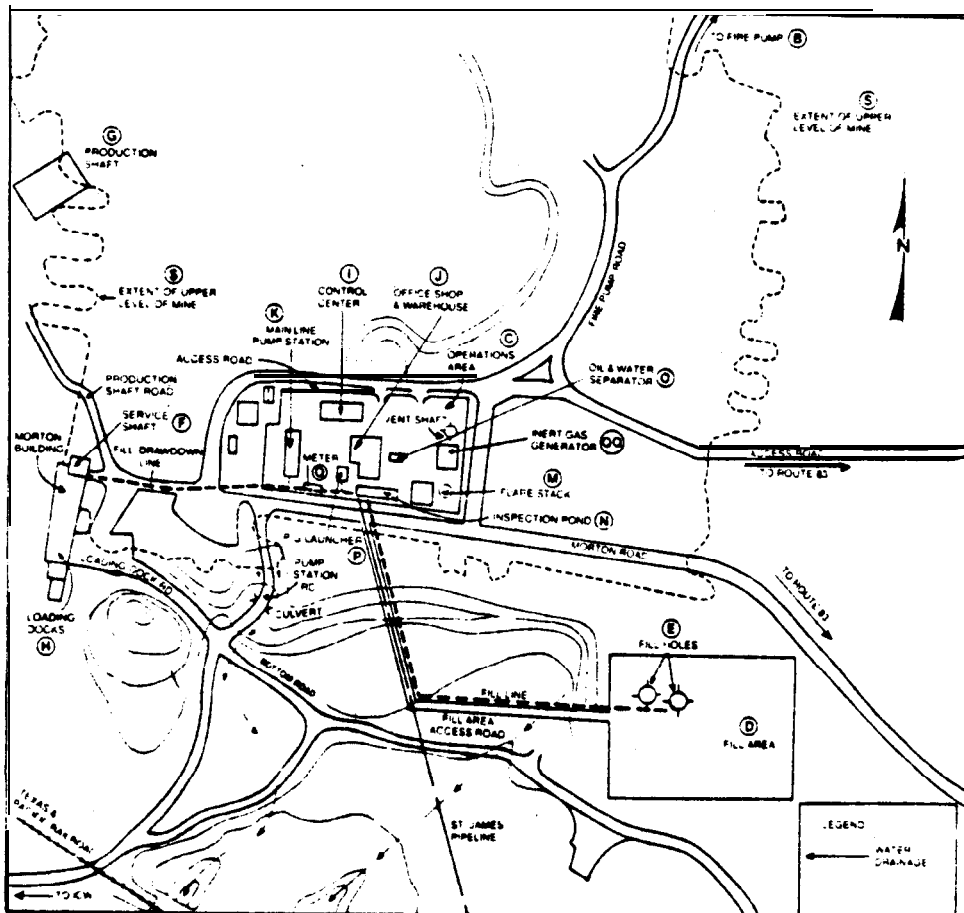


Figure 18- WEEKS ISLAND DETAILED SITE MAP (From U. S. Department of Energy, 1980, Strategic Petroleum Reserve Annual Report)

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